Assessment of the South African sardine resource using data from 1984-2018: Initial results at the joint posterior mode for the two mixing-component hypothesis

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Introduction

The assessment of the South African sardine resource is in the process of being revised and updated using data available up to November 2018. While some data are yet to be finalised and robustness to some key model assumptions is still to be considered, the initial results presented here are expected to be sufficiently accurate such that they can reliably form the basis of simple constant catch projections for short-term management decisions.

The assessment model considers the sardine population to consist of two mixing 'components', with a west component distributed west of Cape Agulhas and a south component distributed south-east of Cape Agulhas. Mixing occurs via movement from the west to the south component in November each year and via some contribution from the south component spawning biomass towards west component recruitment.

Population Dynamics Model

The generalised operating model for the South African sardine resource is used for both the single and two mixing-component hypotheses, and the data used in this assessment are listed in de Moor *et al*. (2019). The model is detailed in Appendix A and all the parameters are defined in Tables A1 and A2. Recruitment is estimated independently each year with no stock-recruitment relationship estimated during conditioning.

Results and Discussion

Natural mortality is assumed to be time-invariant at 1.0 year^{-1} for both juvenile and adult fish. This is an increase of 0.2 year^{-1} for the adult fish from that assumed by de Moor and Butterworth (2016). While the log likelihood difference is not large, the higher natural mortality was selected for these results as it provided an improved fit to the data (Table 1).

The model fit to the time series of survey indices of November biomass and May recruitment are good with no apparent residual trend (Figures 1 and 2). There is no survey estimate of recruitment in 2018. The model fits the November 2018 survey estimate of biomass on the west coast relatively well, though the model predicted biomass on the south coast is towards the upper end of the range of that estimated by the survey.

The multiplicative bias in the surveys is estimated to be 0.73 for the November acoustic survey and 0.47 for the recruit survey on the west coast and 0.44 on the south coast.

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The model estimated annual proportions of age 1 and age 2+ sardine moving from the west to south stock are shown in Figure 3. The proportion of 2+ sardine moving is estimated at the joint posterior mode to be 48%[1] of that of the 1 year olds.

The model estimated survey trawl selectivity is shown in Figure 4 with the residuals from the fit to the November survey length frequency data given in Figure 5. The average model predicted proportions-at-length compare well with those from the survey on the west coast, but not so well on the south coast (Figure 6). As previously postulated, this may be indicative of the hypothesised south coast winter spawning. Allowing for differences in the survey selectivity between components may help improve the fit to these data (see below).

The model estimated commercial selectivity is shown in Figure 7. The years between which commercial selectivity is allowed to differ (1986/7, 1997/8, 2001/2) remain unchanged from those selected for the previous assessment (de Moor and Butterworth 2016). The average (over all years and quarters) model predicted commercial proportions-at-length matches the general pattern of that observed, when assuming that the variability in the normal distribution for small lengths is the same for all years (Figure 9), but further improvement may be realised given different selectivity time-periods (see below).

A key factor in the model fits to the proportion-at-length data is the model estimated growth curve (Figure 10) and variability about this curve (Figure 11). The estimated annual residuals about an average age at which length is zero, chosen to mimic differences between early and late peak recruitment, allow for a better fit to the model. When time allows, an investigation into the 2016 'outlier' will be investigated.

As parasite prevalence-at-length data are available only from 2010 onwards, the infection rate is estimated from 2008 onwards and fixed at an arbitrary rate of zero prior to 2008. The estimated rates of infection of west component sardine by the parasite are estimated to vary substantially between years (Figure 12). The relatively high estimate in 2008 may be due to the model adjusting for no infection assumed prior to that time. Infection is estimated to be low in the most recent two years. The model is able to reflect the observed prevalence-at-length from November surveys sufficiently well (Figure 13).

Figure 14 shows the model estimated November recruitment plotted against the effective spawning biomass (allowing for 8% of the south component spawning biomass to contribute to west coast effective spawning biomass). Figure 15 shows the model estimated exploitation rates, with the exploitation rate on the west component having increased in 2018 to 0.26.

Summary and Future Work

This document has provided an initial 'ball-park' update to the sardine assessment. The model predicted November survey biomass in 2018 was 46 000t on the west coast, compared to the observation of 35 000t, and 204 000t on the south coast,

[1] Note that this point estimate at the joint posterior mode may not be reflective of the marginal posterior distribution (e.g. see de Moor et. al. 2017).

compared to the observation on 56 000t. It estimates the sardine biomass in November 2018 to have been about 345 000t, with the west component consisting of only 63 000t. The west component effective spawning biomass is estimated at about 27 000t in November 2018, with the south component effective spawning biomass at around 97 000t.

A comprehensive assessment of the sardine resource is planned for later during 2019. It is intended that the following should be considered prior to finalising the updated sardine assessment:

- Finalisation of data
- Alternative natural mortality scenarios, including allowance for a change at the turn of the century and allowing differences between the west and south components
- A potential improvement in model fit to data by allowing survey selectivity to differ by component (coast)
- A potential improvement in model fit to data by considering if there are more appropriate breaks (other than 1986/7, 1997/8, 2001/02) between the periods of differing commercial selectivity
- Reconsidering the maturity-at-length relationships over time and potential differences in maturity between the west and south components
- Considering an alternative of modelling west to south movement to occur at 1 August rather than 1 November

References

de Moor CL and Butterworth DS. 2016. Assessment of the South African sardine resource using data from 1984-2015: Results at the joint posterior mode for the two mixing stock hypothesis. DAFF: Branch Fisheries Document FISHERIES/2016/JUL/SWG-PEL/22REV2.

de Moor CL, Butterworth DS and van der Lingen CD. 2017. The quantitative use of parasite data in multistock modelling of South African sardine (*Sardinops sagax*). Canadian Journal of Fisheries and Aquatic Sciences 74:1895-1903.

de Moor CL, Coetzee J, Merkle D and van der Lingen C. 2019. The data used in the 2019 initial sardine assessment. DAFF: Branch Fisheries Document FISHEREIS/2019/APR/SWG-PEL/14.

van der Lingen CD, Fréon P, Fairweather TP, van der Westhuizen JJ. 2006. Density-dependent changes in reproductive parameters and condition of southern Benguela sardine *Sardinops sagax*. African Journal of Marine Science 28(3&4): 625-636.

Table 1. The contributions to the objective function at the posterior mode for two alternative values of adult natural mortality, $\bar{M}_{ad}^{S}$. The ratio of the multiplicative bias in the recruit survey to that in the November survey, k_r^S/k_N^S, is given for diagnostic purposes.

			-ln(Likelihood)					-ln(Prior)					
$\bar{M}_j^S$	$\bar{M}_{ad}^S$	-ln(Posterior)	Nov	Rec	Com Prop-at-length	Survey Prop-at-length	Prevalence	k_{ac}^S	$move_{1,y}$	ε_y^t	k_N^S	k_r^S	k_r^S/k_N^S
1.0	0.8	949.7	59.1	38.5	-426.1	-388.0	1653.2	-1.44	-30.5	44.9	0.73	0.56	0.76
1.0	1.0	946.3	58.3	37.6	-426.2	-392.4	1655.9	-1.43	-30.5	44.9	0.73	0.47	0.65

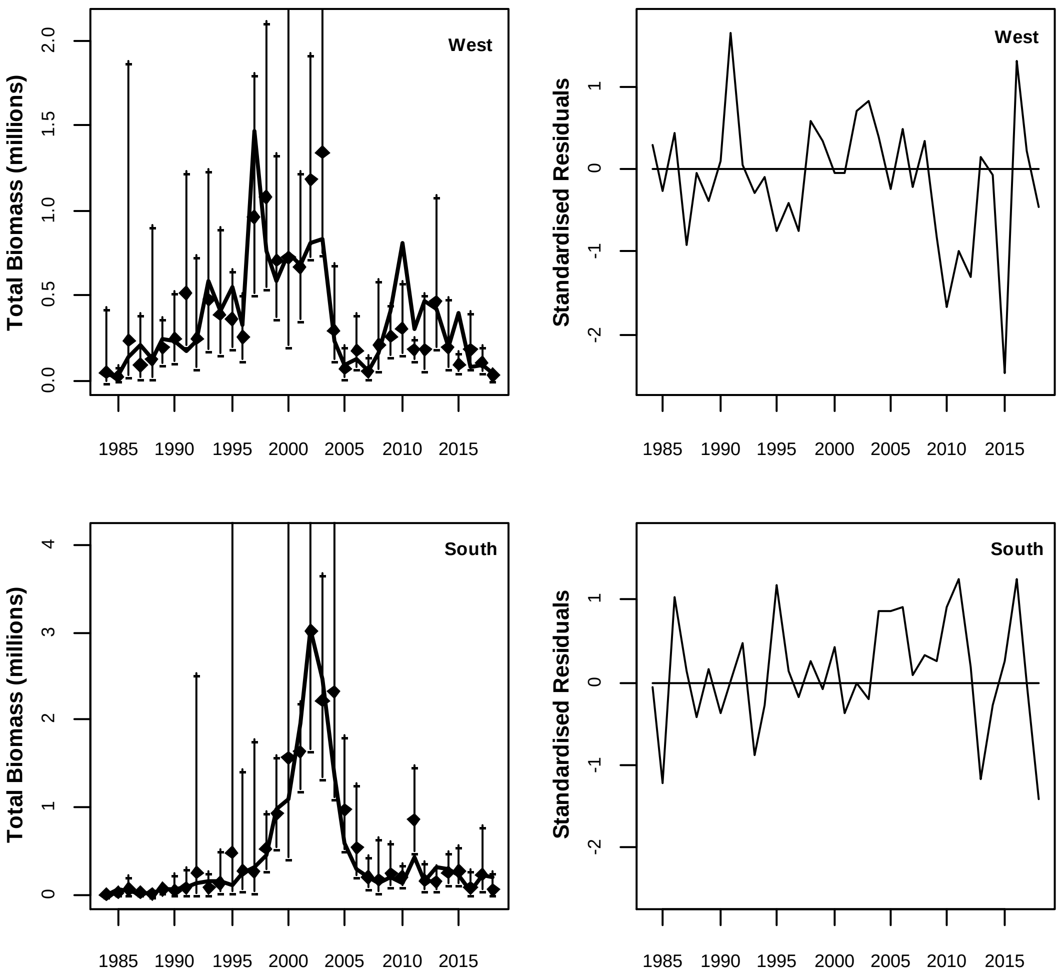

Figure 1. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2018. The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots.

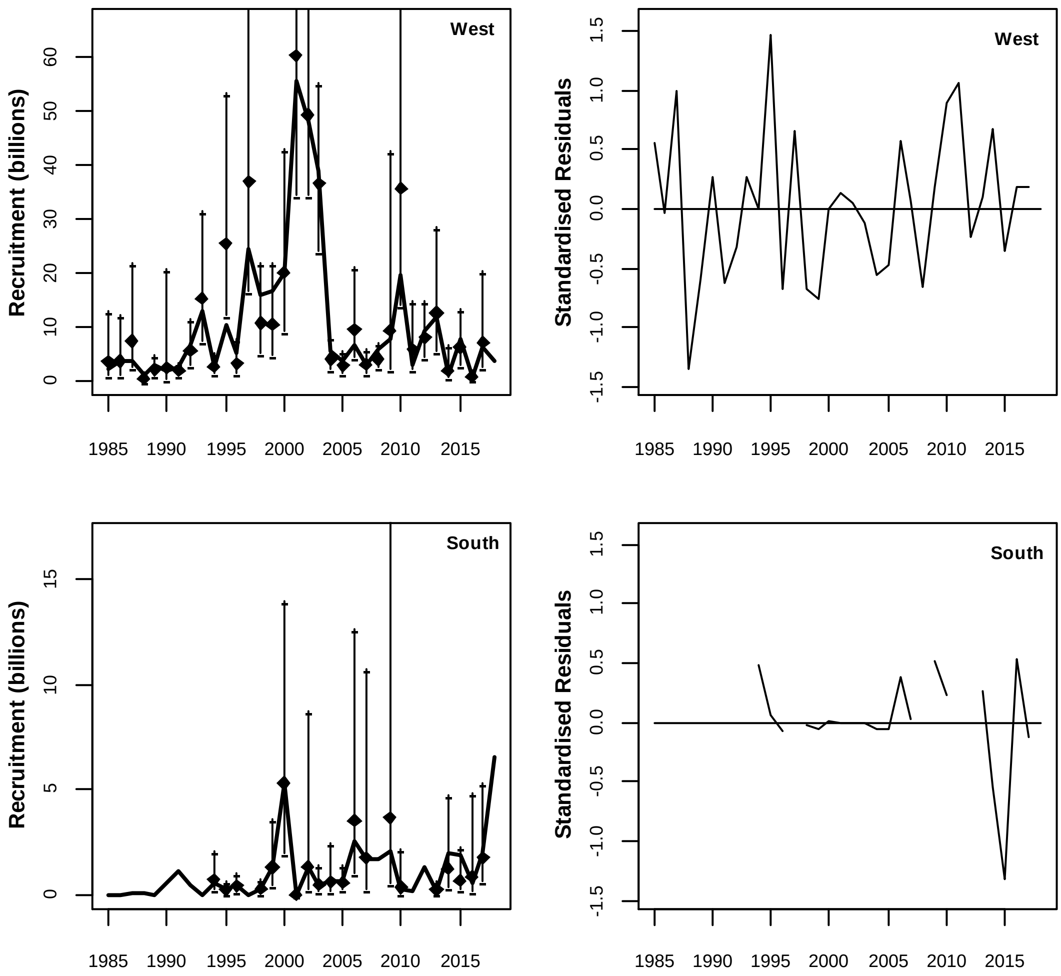

Figure 2. Acoustic survey estimated and model predicted sardine recruitment numbers from May 1985 to May 2018. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots.

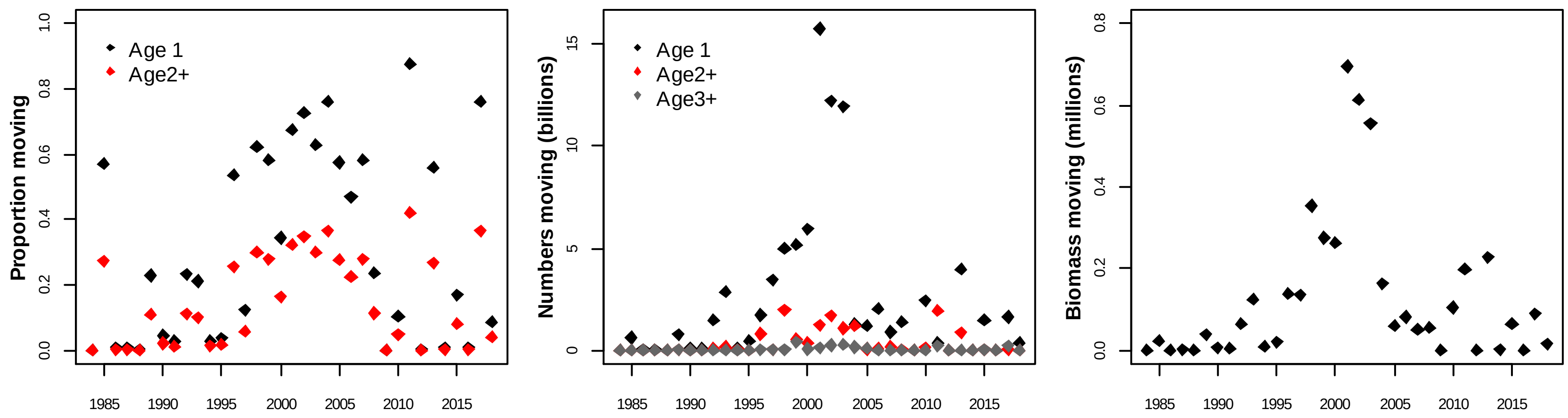

Figure 3. Model estimated proportion of 1-year-olds and 2+-year-olds which move from the "west" component to the "south" component in November. The middle plot shows the numbers of 1-, 2- and 3-year olds moving while the right hand plot shows rough[2] estimates of the annual biomass moving from the west to south component.

[2] Calculated using the average of west and south component weights-at-age.

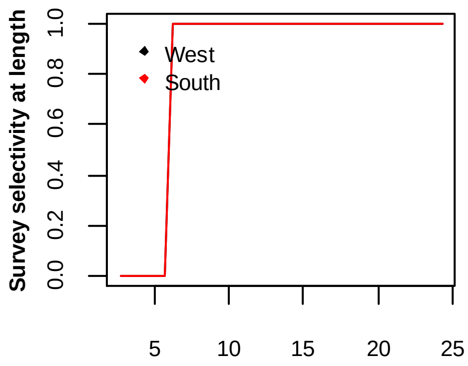

Figure 4. The model estimated November survey selectivity at length.

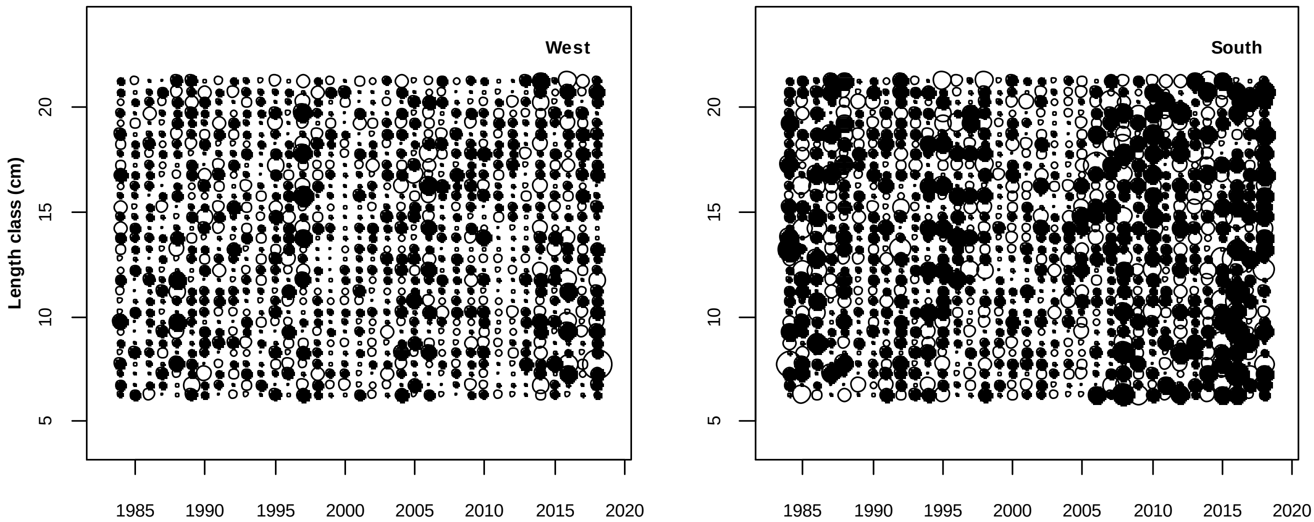

Figure 5. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions.

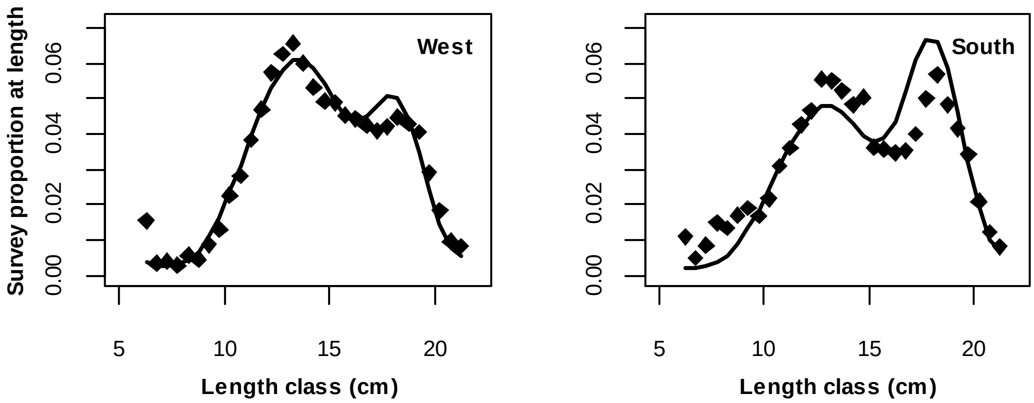

Figure 6. Average (over all years) model predicted and observed proportion-at-length in the November survey.

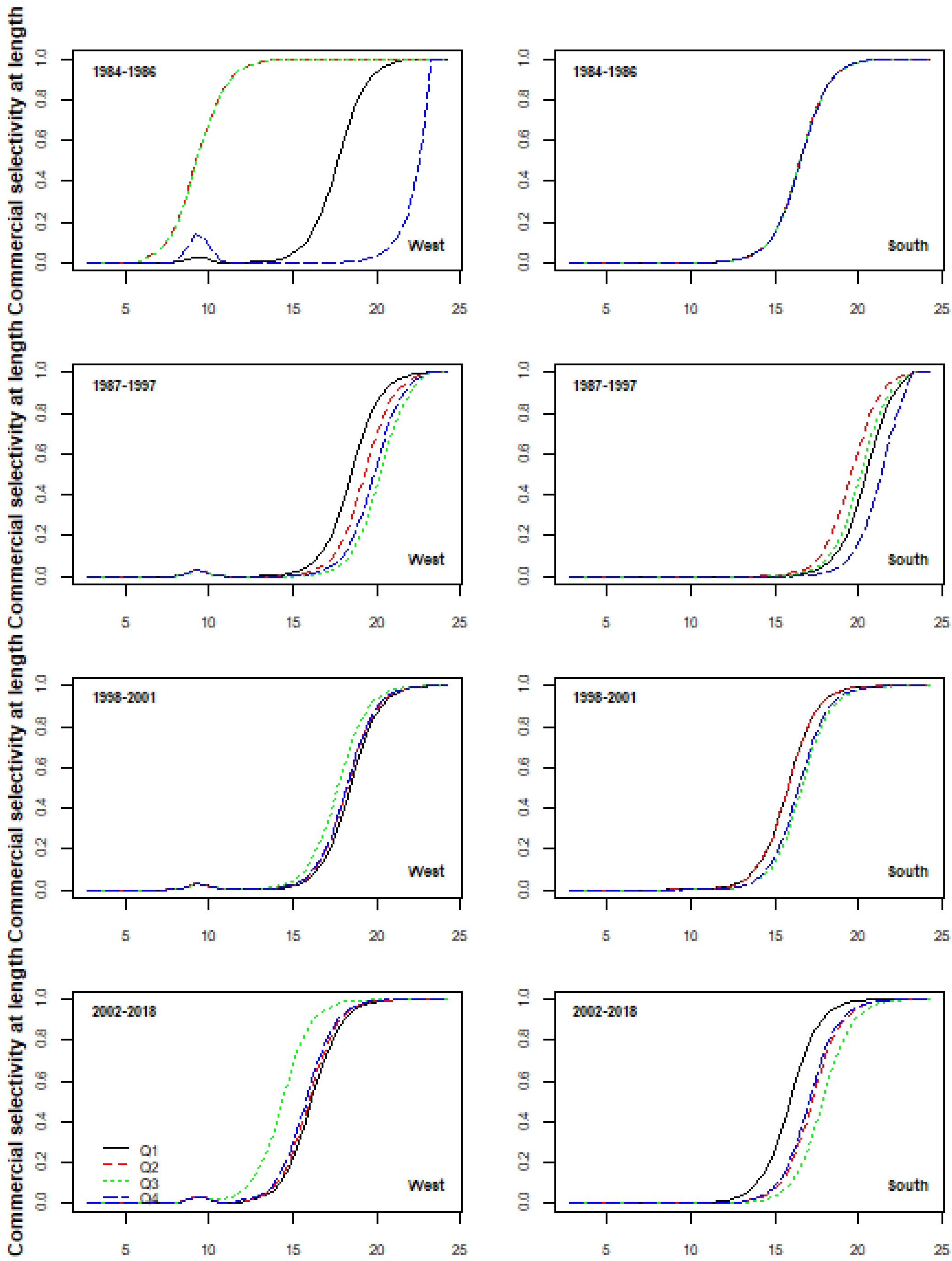

Figure 7. The model estimated commercial selectivity at length, which differs between four pre-specified time periods (the four rows) and quarters.

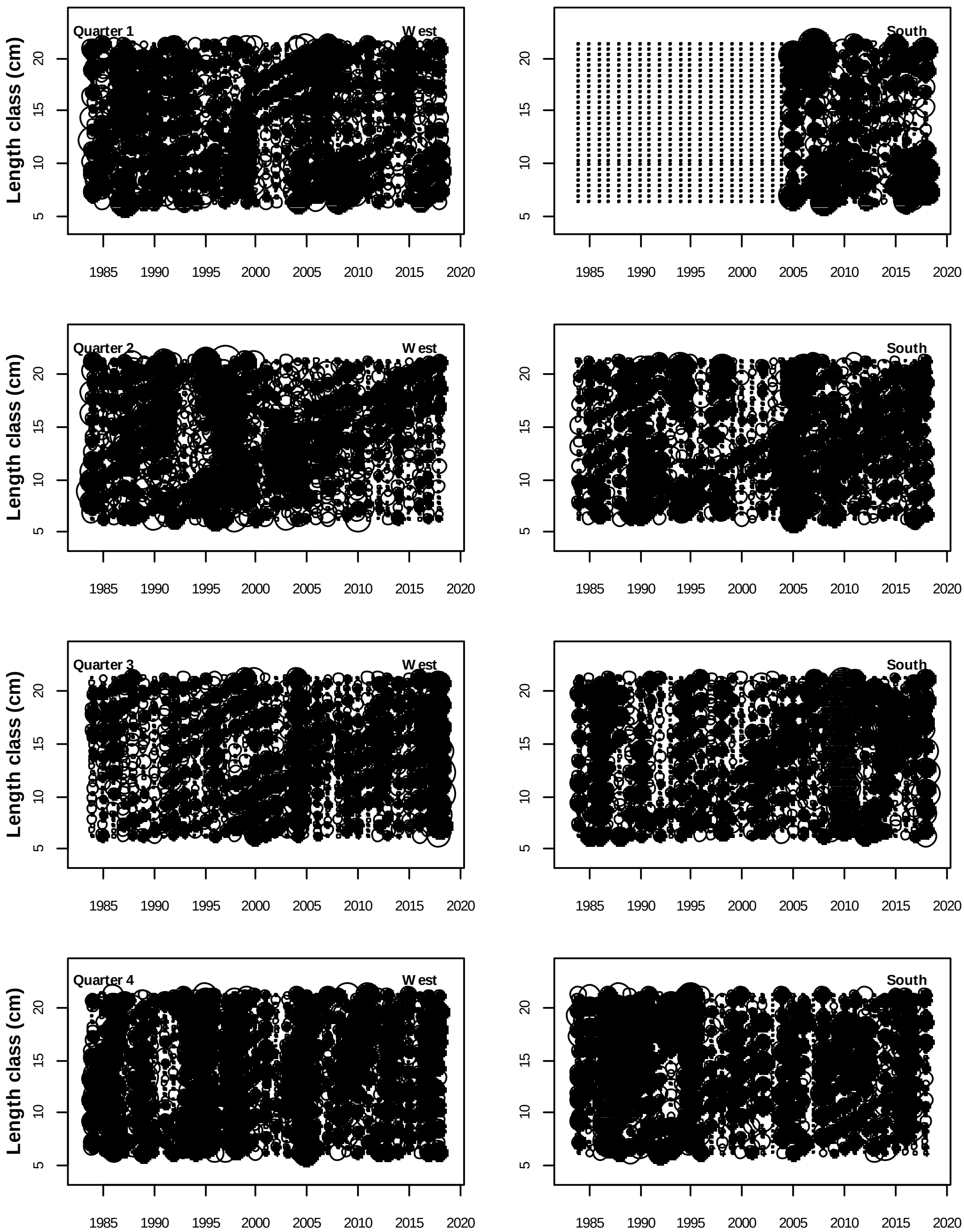

Figure 8. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions.

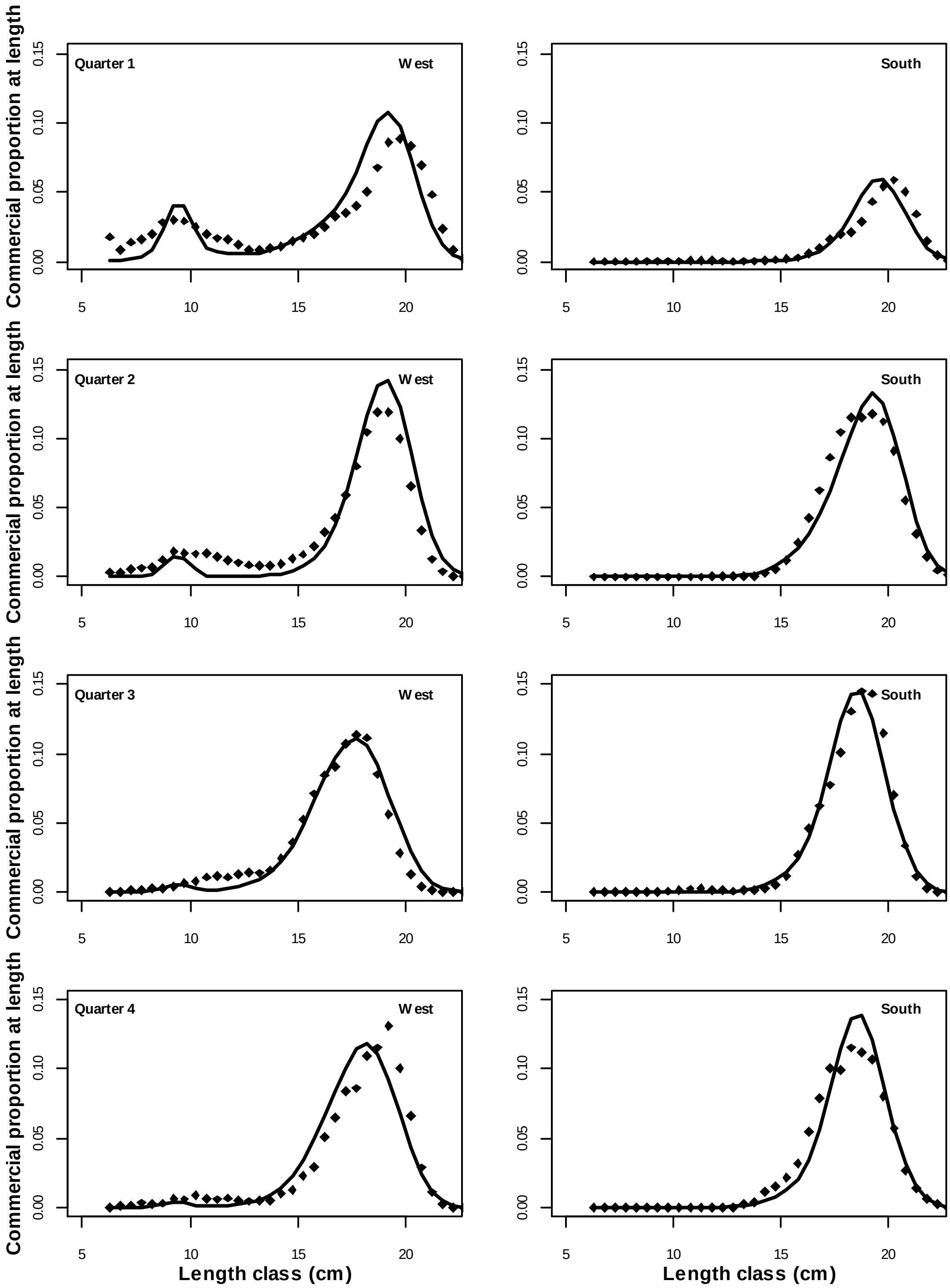

Figure 9. Average (over all quarters and years) model predicted and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted and observed proportions-at-length in the commercial catch (subsequent rows).

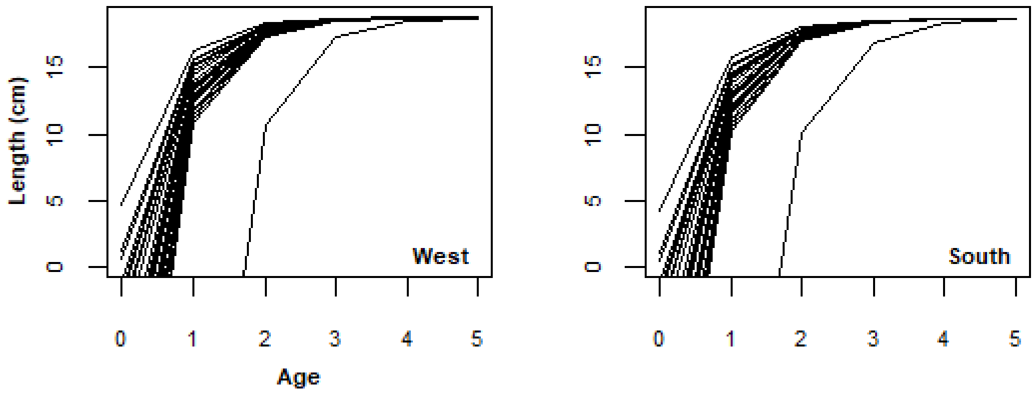

Figure 10. The annual von Bertalanffy growth curves estimated by allowing for auto-correlated residuals for the variation about the age at which length is zero. The rightmost curve corresponds to 2016.

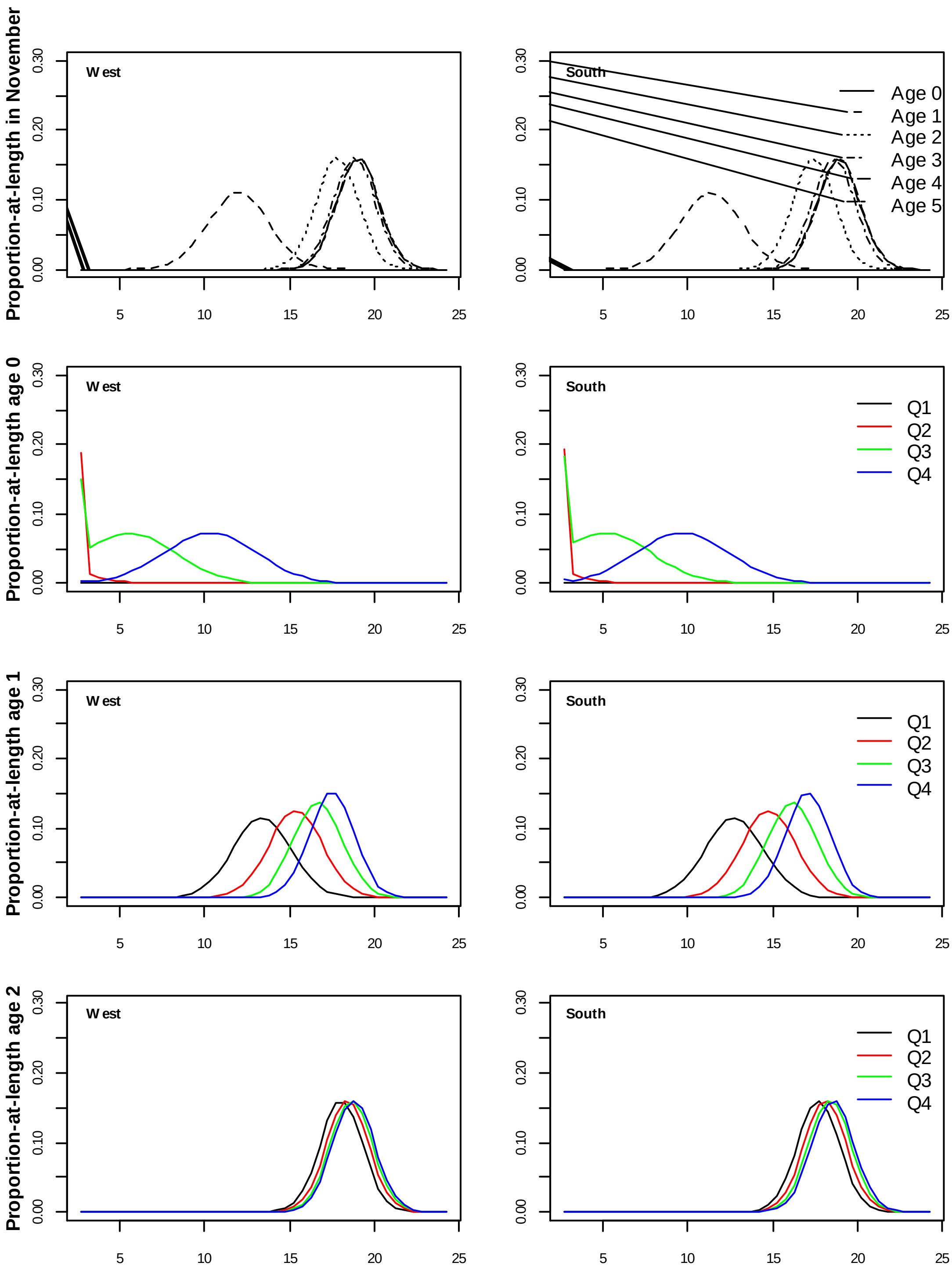

Figure 11. The model estimated distributions of proportions-at-length for each age **in 2010**, given at the time of the biomass survey (1 November, top row), and middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken) for age 0, 1 and 2 (subsequent rows).

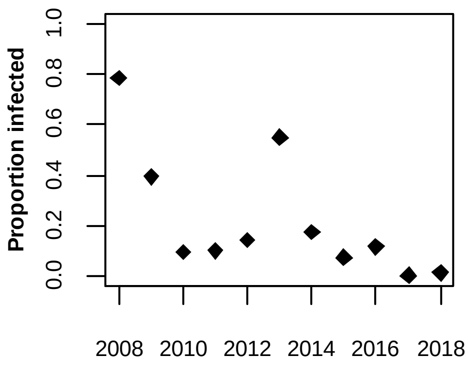

Figure 12. The model estimated proportion of west component sardine infected with the parasite between 2008 and 2018. (Annual infection rate is arbitrarily assumed to be 0 prior to 2008.)

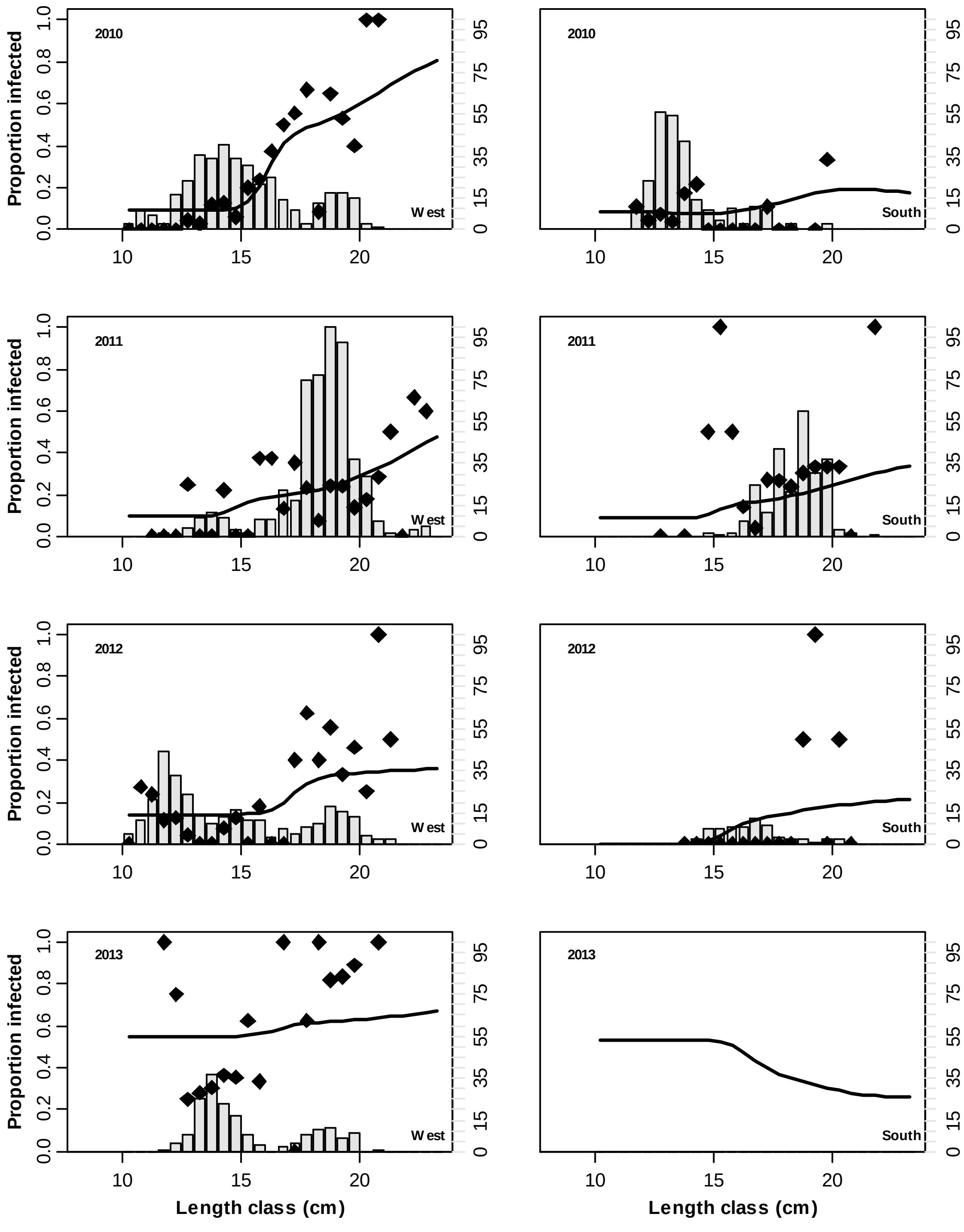

Figure 13. The model estimated proportions-at-length of west and south stock sardine infected with the parasite (i.e. parasite prevalence-by-length) between 2010 and 2018 together with the observed proportions-at-length. The sample size for each length class is given by the grey bars, plotted against the right vertical axis.

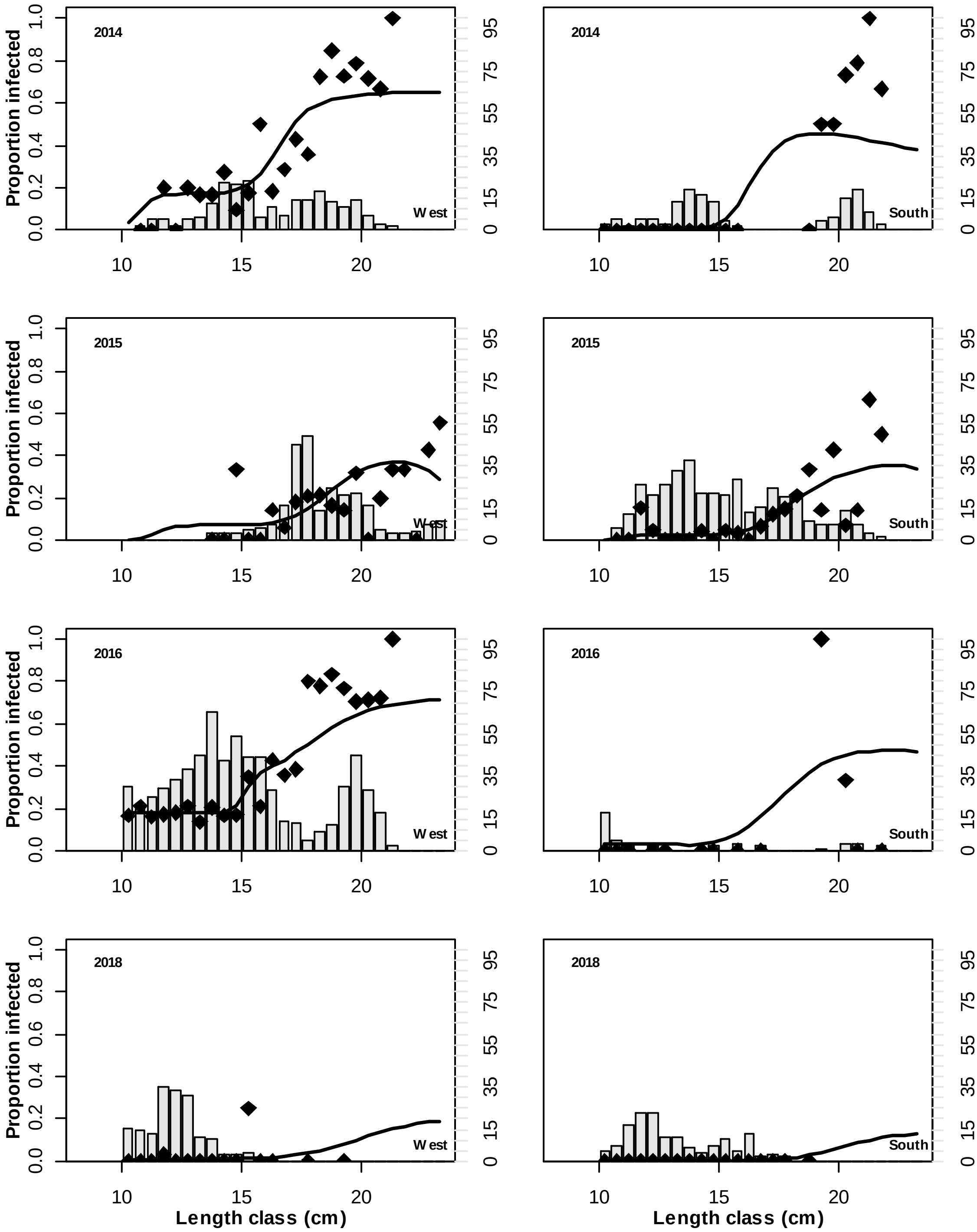

Figure 13 (continued).

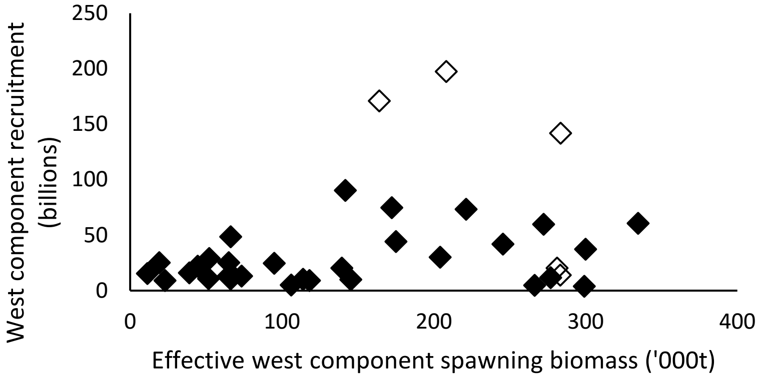

Figure 14. Model predicted sardine recruitment (in November) plotted against effective spawner biomass from November 1984 to November 2017.

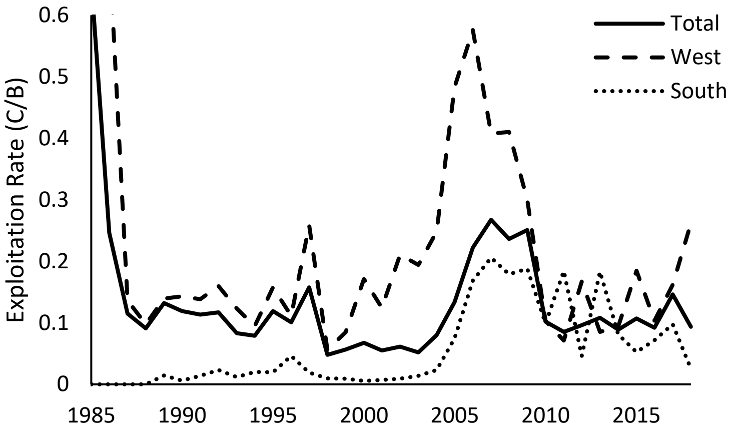

Figure 15. The exploitation rate (simply calculated as the observed annual (Nov-Oct) catch tonnage as a proportion of the model predicted total biomass).

Appendix A: Bayesian assessment model for the South African sardine resource

The assessment is run from November $y_1 = 1984$ to November $y_n = 2018$, with the following subscript notation:

- quarters $q = 1$ denoting November $y-1$ to January y, $q = 2$ denoting February to April y, $q = 3$ denoting May to July y and $q = 4$ denoting August to October y;
- ages $a = 0$ to a plus group of $a = 5^+$;
- lengths from a minus group of $l = 2.5^- cm$ to a plus group of $l = 24^+ cm$;
- components $j = W$ or $j = S$ denote the west and south components, respectively, where only the west component equations are used in the single component hypothesis;
- infection $p = NI$ or $p = I$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

All parameters are defined in Tables A1 and A2.

Population Dynamics

Numbers-at-age at 1 November before movement or infection

$$N_{j,p,y,a}^{S*} = \left(\left(\left(\left(N_{j,p,y-1,a-1}^{S} e^{-M_{y,a-1}^{S}/8} - C_{j,p,y,1,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,2,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,3,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,4,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/8}$$

$$p = I, NI, y_1 \leq y \leq y_n, 1 \leq a \leq 4$$

$$N_{j,p,y,5^+}^{S*} = \left(\left(\left(\left(N_{j,p,y-1,4}^{S} e^{-M_{y,4}^{S}/8} - C_{j,p,y,1,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,2,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,3,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,4,4}^{S}\right) e^{-M_{y,4}^{S}/8} +$$
$$\left(\left(\left(\left(N_{j,p,y-1,5^+}^{S} e^{-M_{y,5^+}^{S}/8} - C_{j,p,y,1,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,2,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,3,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,4,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/8}$$

$$p = I, NI, y_1 \leq y \leq y_n \qquad \text{(A1)}$$

Infection of west component sardine in the two mixing-component hypothesis; in the single component hypothesis $I_y = 0$ *as the parasite data have no influence so that they are not included in the likelihood*

$$\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S**}} = \left(1 - \mathrm{I_y}\right)\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S*}} \qquad y_1 \leq y \leq y_n, 1 \leq a \leq 5^+$$
$$\mathrm{N}_{\mathrm{W,I,y,a}}^{\mathrm{S**}} = \mathrm{N}_{\mathrm{W,I,y,a}}^{\mathrm{S*}} + \mathrm{I_y}\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S*}} \qquad y_1 \leq y \leq y_n, 1 \leq a \leq 5^+$$
$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S**}} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S*}} \qquad p = I, NI, y_1 \leq y \leq y_n, 1 \leq a \leq 5^+ \qquad \text{(A2)}$$

Movement of west component ($j = W$) sardine to the south component ($j = S$) in the two mixing-component hypothesis; in the single component hypothesis $move_{y,a} = 0$

$$\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S}} = \left(1 - \mathrm{move_{y,a}}\right)\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \leq y \leq y_n, 1 \leq a \leq 5^+$$
$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S**}} + \mathrm{move_{y,a}}\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \leq y \leq y_n, 1 \leq a \leq 5^+ \qquad \text{(A3)}$$

Numbers-at-age mid-way through each quarter (for use in catch equations)

$$N_{j,p,y,1,a}^{S} = N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/8} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$
$$N_{j,p,y,q,a}^{S} = \left(N_{j,p,y,q-1,a}^{S} - C_{j,p,y,q-1}^{S}\right) e^{-M_{y,a}^{S}/4} \qquad p = I, NI, y_1 \leq y \leq y_n, 2 \leq q \leq 4, 0 \leq a \leq 5^+ \qquad \text{(A4)}$$

Numbers-at-length at 1 November (after infection and movement)

The model estimated numbers-at-length range from a 2.5cm minus group to a 24cm plus group, denoted 2.5^- and 24^+, respectively, in the remaining text.

$$N^S_{j,p,y,l} = \sum_{a=0}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \quad \text{(A5)}$$

The model predicted numbers-at-length of ages 1+ only are given by:

$$N^{S,1+}_{j,p,y,l} = \sum_{a=1}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \quad \text{(A6)}$$

The proportion of sardine of age a in component j that fall in length group l at 1 November, $A^{sur}_{j,y,a,l}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A^{sur}_{j,y,a,l} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j (a - t_{0,j,y})}\right), \vartheta_a^2\right)^{3} \qquad y_1 \le y \le y_n,\ 0 \le a \le 5^+,\ 2.5^- cm \le l \le 24^+ cm \quad \text{(A7)}$$

with

$$t_{0,j,y} = \begin{cases} t_{0,j} + \varepsilon^t_y & y = y_1 \\ t_{0,j} + \rho^t \varepsilon^t_{y-1} + \sqrt{1 - (\rho^t)^2}\,\varepsilon^t_y & y_1 < y \le y_n \end{cases} {}^{4} \quad \text{(A8)}$$

Natural mortality

Natural mortality is modelled to vary annually in an autocorrelated manner around a median as follows (although the baseline assumes no such correlation – see Table A.1):

$$M^S_{y,a=0} = \bar{M}^S_{ju} e^{\varepsilon^{ju}_y} \text{ with } \varepsilon^{ju}_{1984} = \eta^{ju}_{1984} \text{ and } \varepsilon^{ju}_y = \rho \varepsilon^{ju}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ju}_y,\ y_1 \le y \le y_n \quad \text{(A9)}$$

$$M^S_{y,a=1+} = \bar{M}^S_{ad} e^{\varepsilon^{ad}_y} \text{ with } \varepsilon^{ad}_{1984} = \eta^{ad}_{1984} \text{ and } \varepsilon^{ad}_y = \rho \varepsilon^{ad}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ad}_y,\ y_1 \le y \le y_n \quad \text{(A10)}$$

Spawning biomass and biomass associated with the November survey

$$SSB^S_{j,y} = \sum_p \sum_{l=2.5^-}^{24^+} f^S_{j,y,l} N^{S,1+}_{j,p,y,;} w^S_{j,y,l} \qquad y_1 \le y \le y_n \quad \text{(A11)}$$

$$SSB^{eff,S}_{j=W,y} = \xi_W SSB^S_{W,y} + (1 - \xi_S) SSB^S_{S,y} \qquad y_1 \le y \le y_n$$

$$SSB^{eff,S}_{j=S,y} = (1 - \xi_W) SSB^S_{W,y} + \xi_S SSB^S_{S,y} \qquad y_1 \le y \le y_n \quad \text{(A12)}$$

$$B^S_{j,y} = k^S_{j,N} \sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} w^S_{j,y,l}\ {}^{5} \qquad y_1 \le y \le y_n \quad \text{(A13)}$$

$$\text{where } w^S_{j,y,l} = w^S_{j,l} \times \frac{\tilde{w}_{j,y}}{\left(\sum_p \sum_{l=2.5^-}^{24^+} N^{S,1^+}_{j,p,y,l} w^S_{j,l}\right) / \left(\sum_p \sum_{l=2.5^-}^{24^+} N^{S,1^+}_{j,p,yl;}\right)} \qquad y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \quad \text{(A14)}$$

Commercial selectivity

$$S_{j,y,q,l} = \begin{cases} 0 & l \le 5.5cm \\ \chi_j exp\left\{-\dfrac{\left(l + 0.25 - \bar{l}_{1,j}\right)^2}{(\sigma^{sel}_1)^2}\right\} + \dfrac{1}{1 + exp\left\{-\left(l + 0.25 - \bar{l}_{2,j,y,q}\right)/(\sigma^{sel}_2)^2\right\}} & 6cm \le l \le l_{max} = 23cm\ {}^{6} \\ S_{j,y,q,lmax} & l > l_{max} \end{cases}$$

$$y_1 \le y \le y_n,\ 1 \le q \le 4 \quad \text{(A15)}$$

[3] Given the allowance for early/late recruitment in varying $t_{0,y}$ estimates annually, there may be some proportion of this distribution below a length of zero (due to late recruitment). In these cases, this proportion is removed from the proportion-at-length of the minus length class.

[4] Additive error allows for early or late recruitment. While the timing of recruitment may vary between stocks due to differing environmental conditions on the west and south coasts, the same autocorrelation parameters are assumed here for simplicity reasons.

[5] The biomass in $y_n = 2018$ excludes age 0 fish, although the contribution of age 0 fish to the total biomass should be minor.

[6] The $l + 0.25$ denotes the middle of length class l. This function is renormalized to a maximum of 1.

$$S_{j,y,q,a} = \sum_{l=2.5^-}^{24^+} A_{j,y,q,a,l}^{com} S_{j,y,q,l} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4,\ 0 \le a \le 5^+ \qquad \text{(A16)}$$

where $A_{j,y,q,a,l}^{com} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j\left(a+(2q-1)/8-t_{0,j,y}\right)}\right), \left[\left(1-(2q-1)\right)\vartheta_a + (2q-1)\vartheta_{a+1}\right]^2\right)$

$$y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A17)}$$

Bycatch in the anchovy directed fishery

$$C_{j,p,y,q,a}^{bycatch} = \begin{cases} N_{j,p,y,q,a}^{S} F_{j,y,q,a}^{By} & 0 \le a \le 1 \\ 0 & 2 \le a \le 5^+ \end{cases} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4 \qquad \text{(A18)}$$

[7]

Catch in the directed sardine and round herring bycatch fisheries

$$C_{j,p,y,q,a}^{dir} = \left(N_{j,p,y,q,a}^{S} - C_{j,p,y,q,a}^{bycatch}\right) S_{j,y,q,a} F_{j,y,q} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A19)}$$

Total catch

$$C_{j,p,y,q,a}^{S} = C_{j,p,y,q,a}^{bycatch} + C_{j,p,y,q,a}^{dir} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A20)}$$

Fished proportion of the available biomass from the sardine bycatch with the anchovy directed fishery

$$F_{j,y,q=1,a=0}^{By} = \frac{\sum_{m=11}^{12} \sum_{l<lcut_{y-1,m}} C_{j,y-1,m,l}^{RLF,fleet=3} + \sum_{l<lcut_{y,m}} C_{j,y,1,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=1,a=0}^{S}}$$

$$F_{j,y,q=1,a=1}^{By} = \frac{\sum_{m=11}^{12} \sum_{l\ge lcut_{y-1,m}} C_{j,y-1,m,l}^{RLF,fleet=3} + \sum_{l\ge lcut_{y,m}} C_{j,y,1,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=1}^{S}}$$

$$F_{j,y,q=2,a=0}^{By} = \frac{\sum_{m=2}^{4} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=2,a=0}^{S}} \qquad F_{j,y,q=2,a=1}^{By} = \frac{\sum_{m=2}^{4} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=2,a=1}^{S}}$$

$$F_{j,y,q=3,a=0}^{By} = \frac{\sum_{m=5}^{7} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=3,a=0}^{S}} \qquad F_{j,y,q=3,a=1}^{By} = \frac{\sum_{m=5}^{7} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=3,a=1}^{S}}$$

$$F_{j,y,q=4,a=0}^{By} = \frac{\sum_{m=8}^{10} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=0}^{S}} \qquad F_{j,y,q=4,a=1}^{By} = \frac{\sum_{m=8}^{10} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=1}^{S}} \qquad \text{(A21)}$$

A penalty is imposed within the model to ensure that $F_{j,y,q,a}^{By} < 0.95$.

Fished proportion of the available biomass from the directed sardine catch and sardine bycatch with round herring fishery

$$F_{j,y,q=1} = \frac{\sum_{fleet=1}^{2} \sum_{m=11}^{12} \sum_{l\ge 6cm} C_{j,y-1,m,l}^{RLF,fleet} + \sum_{fleet=1}^{2} \sum_{l\ge 6cm} C_{j,y,1,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,1,a}^{S} - C_{j,y,1,a}^{bycatch}\right) S_{j,y,1,a}}$$

$$F_{j,y,q=2} = \frac{\sum_{fleet=1}^{2} \sum_{m=2}^{4} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,2,a}^{S} - C_{j,y,2,a}^{bycatch}\right) S_{j,y,2,a}}$$

$$F_{j,y,q=3} = \frac{\sum_{fleet=1}^{2} \sum_{m=5}^{7} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,3,a}^{S} - C_{j,y,3,a}^{bycatch}\right) S_{j,y,3,a}}$$

$$F_{j,y,q=4} = \frac{\sum_{fleet=1}^{2} \sum_{m=8}^{10} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,4,a}^{S} - C_{j,y,4,a}^{bycatch}\right) S_{j,y,4,a}} \qquad \text{(A22)}$$

[7] "Selectivity" is incorporated in $F_{j,y,q,a}^{By}$, as the sardine bycaught is typically independent of sardine abundance, but rather correlated with anchovy recruitment which varies from year to year.

A penalty is imposed within the model to ensure that $S_{j,y,a,l}F_{j,y,q} < 0.95$. Fish <6cm were seldom[8] caught and were thus not used in fitting this model. Commercial selectivity-at-length is fixed to zero for length classes <6cm (equation A12).

Number of recruits associated with the recruit survey

$$N^S_{j,y,r} = k^S_{j,r}\left(\left(N^S_{j,NI,y,2,0} - C^S_{j,NI,y,2,0}\right)e^{-(1/8+0.5t^S_y/12)M^S_{y,0}} - \tilde{C}^S_{j,y,0bs}\right)e^{-0.5t^S_y \times M^S_{y,0}/12} \quad 1985 \le y \le y_n \qquad \text{(A23)}$$

Multiplicative survey bias

$$k^S_{j,N} = k^S_{ac} \qquad \text{(A24)}$$

$$k^S_{j=W,r} = k^S_{cov} \times k^S_{ac} \qquad \text{(A25)}$$

$$k^S_{j=S,r} = k^S_{covS} \times k^S_{cov} \times k^S_{ac} \quad \text{(for the two mixing-component hypothesis only)} \qquad \text{(A26)}$$

Survey trawl selectivity

$$S^{survey}_{j,l} = \begin{cases} 0 & l = 2.5^- cm \\ [1 + exp\{-(l + 0.25 - S_{50})/\delta\}]^{-1} & 3cm \le l \le 24^+ cm \end{cases} \qquad y_1 \le y \le y_n \qquad \text{(A27)}$$

Proportion-at-length associated with the November survey

$$p^s_{j,y,l} = \begin{cases} \dfrac{\sum_p \sum_{l \le 6cm} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 6^- cm \\ \dfrac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & 6.5cm \le l \le 20.5cm \\ \dfrac{\sum_p \sum_{l=21}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 21 - 23.5cm \\ \dfrac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,24^+}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 24^+ cm \end{cases} \text{[9]} \qquad y_1 \le y \le y_n \qquad \text{(A28)}$$

Proportion-at-length of fish infected with the parasite in November

$$P^S_{j,y,l} = \frac{N^S_{j,I,y,l}}{\sum_p N^S_{j,p,y,l}} \qquad y_1 \le y \le y_n, 10cm \le l \le 23cm \qquad \text{(A29)}$$

Catch-at-length from the directed and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5^+}\left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right)A^{com}_{j,q,a,l}S_{j,y,q,l}F_{j,y,q} \text{[10]}$$

$$p = I, NI, y_1 \le y \le y_n, 1 \le q \le 4, 2.5^- cm \le l \le 24^+ cm \qquad \text{(A30)}$$

[8] Less than 6% of the quarters west of Cape Agulhas, less than 2% of the quarters south-east of Cape Agulhas and less than 4% of the quarters for the whole coast.

[9] The inclusion of model predicted proportion-at-length 24+cm is deliberate to take into account the zero samples of 24+cm sardine in the survey.

[10] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

Proportion-at-length associated with the directed catch and round herring bycatch

$$p^{coml,S}_{j,y,q,l} = \begin{cases} \frac{\sum_p C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & 6cm \le l \le 22.5cm \\ \frac{\sum_p \sum_{l=23}^{24^+} C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & l = 23^+cm \end{cases} \quad [11] \quad y_1 \le y \le y_n,\ 1 \le q \le 4 \tag{A31}$$

<u>Fitting the Model to Observed Data (Likelihood)</u>

$$-lnL = -lnL^{Nov} - lnL^{rec} - lnL^{sur\ propl} - lnL^{com\ propl} - lnL^{prev} \tag{A32}$$

where

$$-lnL^{Nov} = 0.5 \sum_j \sum_{y=y_1}^{y_n} \left\{ \frac{5^5 \left(\frac{\left| ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5}{5^5 + \left(\frac{\left| ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi \left(\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2 \right) \right] \tag{A33}$$

$$-lnL^{rec} = 0.5 \sum_j \sum_{y=y_2}^{y_n} \left\{ \frac{5^5 \left(\frac{\left| ln\left(\hat{N}^S_{j,y,r}\right) - ln\left(N^S_{j,y,r}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,r}\right)^2}} \right)^5}{5^5 + \left(\frac{\left| ln\left(\hat{N}^S_{j,y,r}\right) - ln\left(N^S_{j,y,r}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,r}\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi \left(\left(\sigma^S_{j,y,rec}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,r}\right)^2 \right) \right] \tag{A34}$$

$$-lnL^{sur\ propl} = w^{sur}_{propl} \sum_j \sum_{y=y_1}^{y_n} \left\{ \sum_{l=6}^{21^+} \left\{ \frac{\left(\sqrt{\hat{p}^S_{j,y,l}} - \sqrt{p^S_{j,y,l}} \right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} + \frac{\left(0 - \sqrt{p^S_{j,y,24^+}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} \quad [12] \tag{A35}$$

$$-lnL^{com\ propl} = w^{com}_{propl} \sum_j \sum_{y=y_1}^{y_n} \sum_{q=1}^{4} \sum_{l=6}^{23^+} \left\{ \frac{\left(\sqrt{\hat{p}^{S,coml}_{j,y,q,l}} - \sqrt{p^{S,coml}_{j,y,q,l}} \right)^2}{2\left(\sigma^S_{j,com}\right)^2} + ln\left(\sigma^S_{j,com}\right) \right\} \tag{A36}$$

$$-lnL^{prev} = \sum_j \sum_{y=2010}^{2018} \sum_{l=10cm}^{23cm} -n^{prev}_{j,y,l} ln\left(P^S_{j,y,l}\right) - \left(N^{prev}_{j,y,l} - n^{prev}_{j,y,l}\right) ln\left(1 - P^S_{j,y,l}\right) \tag{A37}$$

A "robustified likelihood" is used for the contributions from the hydro-acoustic surveys to ensure no undue influence from any extreme (outlying) values for residuals. The functional form chosen to robustify makes negligible difference for standardised residuals of magnitude three or less, but essentially treats large standardised residuals as if they do not exceed five in magnitude.

[11] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

[12] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.

Table A1. Assessment model parameters and variables with associated fixed values or prior distributions and, for derived variables, associated equation numbers. As the majority of prior distributions are uninformative, notes are provided only for informative priors and/or bounds.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N^S_{j,p,y,a}$	Model predicted numbers-at-age a at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions	$ln(N^S_{j,NI,y,0})/10 \sim U(-10,3.$ $N^S_{j,I,y,0} = 0$	A1 - A3	
	$N^S_{j,p,1983,a}$	Initial numbers-at-age a in component j	Billions	$N^S_{j,NI,1983,a=1} \sim U(0,50)$ $N^S_{j,NI,1983,a} = 0,\ 2 \leq a \leq 5^+$ $N^S_{j,I,1983,a} = 0,\ 0 \leq a \leq 5^+$		
	$N^S_{j,p,y,q,a}$	Model predicted numbers-at-age a mid-way through quarter q of year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A4	
	I_y	Proportion of uninfected west component sardine that are infected with the endoparasite in year y (two mixing-component hypothesis only)		$= 0,\ y_1 \leq y \leq 2007$ $\sim U(0,1),\ 2008 \leq y \leq y_n$		
	$move_{y,a}$	Proportion of west component sardine of age a which move to the south component at the beginning of November of year y (two mixing-component hypothesis only)	-	$move_{y,1} \sim Beta(1.05,1.05)$ $move_{y,2+} = \phi move_{y,1}$ $\phi \sim U(0,1)$		
	$SSB^S_{j,y}$	Model predicted spawning biomass of component j at the beginning of November in year y	Thousand tons		A11	
	$SSB^{eff,S}_{j,y}$	Model predicted effective spawning biomass of component j at the beginning of November in year y	Thousand tons		A12	
	$B^S_{j,y}$	Model predicted total biomass of component j at the beginning of November in year y, associated with the November survey	Thousand tons		A13	
	ξ_j	Proportion of j-component spawner biomass that contributes to the effective spawning biomass on the same coast		0.08		Alternative values considered in robustness tests
	$w^S_{j,l}$	Mean mass of sardine of component j in length class l	Grams	$1.1639 \times 10^{-5} \times l^{3.03155}$		van der Lingen *et al.* (2006)
	$w^S_{j,y,l}$	Mean mass of sardine of component j in length class l at the beginning of November in year y	Grams		A14	
	$\widetilde{w}^S_{j,y}$	Mean mass of sardine sampled from component j during the November survey of year y	Grams	$\frac{\sum_{l=3}^{23.5} N^{S,obs}_{j,y,l} w^S_{j,l}}{\sum_{l=3}^{23.5} N^{S,obs}_{j,y,l}}$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$f_{j,y,l}^{S}$	Proportion of component j sardine that are mature in length class l in year y	-	$\left[1+e^{-(l-17.2)/1.17}\right]^{-1}$ $1984 \leq y \leq 1987$ $\left[1+e^{-(l-18.6)/1.26}\right]^{-1}$ $1988 \leq y \leq 1995$ $\left[1+e^{-(l-19.4)/1.40}\right]^{-1}$ $1996 \leq y \leq 2003$ $\left[1+e^{-(l-17.4)/0.95}\right]^{-1}$ $2004 \leq y \leq 2018$		Refit from data used by van der Lingen *et al*. (2006) using midpoints of length classes. Assuming maturity post-2003 reflects that of 1965-1975 as maturity is hypothesized to be density dependent (van der Lingen *et al*. 2006) and both these periods correspond to low biomass following a peak in abundance
	$N_{j,y,r}^{S}$	Model predicted number of juveniles of component j at the time of the recruit survey in year y	Billions		A23	
Natural mortality	$M_{y,a}^{S}$	Rate of natural mortality of age a in year y	Year^{-1}	$M_{y,0}^{S}=1.0$ $M_{y,1+}^{S}=1.0$	A9 and A10	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\bar{M}_{ju}^{S}$	Median juvenile rate of natural mortality	Year^{-1}	1.0		
	$\bar{M}_{ad}^{S}$	Median rate of natural mortality for 1+ sardine	Year^{-1}	0.8		
	ε_{y}^{ju}	Annual residuals about juvenile natural mortality rate	-		A9	
	ε_{y}^{ad}	Annual residuals about natural mortality rate for 1+ sardine	-		A10	
	η_{y}^{ju}	Normally distributed error in calculating ε_{y}^{ju}	-	$N(0,\sigma_{j}^{2})$		
	η_{y}^{ad}	Normally distributed error in calculating ε_{y}^{ad}	-	$N(0,\sigma_{ad}^{2})$		
	σ_{j}	Standard deviation in the annual residuals about juvenile natural mortality	-	0		See robustness tests
	σ_{ad}	Standard deviation in the annual residuals about natural mortality for ages 1+	-	0		See robustness tests
	ρ	Annual autocorrelation coefficient	-	0		See robustness tests

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Proportions-at-length and growth curve	$N_{j,p,y,l}^{S}$	Model predicted numbers-at-length l at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A5	
	$p_{j,y,l}^{S}$	Model predicted proportion-at-length l of component j associated with the November survey in year y	-		A28	
	$A_{j,y,a,l}^{sur}$	Proportion of age a of component j sardine that falls in the length group l in November of year y	-		A7	
	κ_j	Somatic growth rate parameter for component j	Year^{-1}	$U(0{,}3)$		
	$L_{j,\infty}$	Maximum length (in expectation) of component j	Cm	$L_{j,\infty} = \frac{L_{j,1}e^{-2\kappa_j} - L_{j,3}}{e^{-2\kappa_j} - 1}$ where $L_{j,a=1} \sim U(5{,}25)$ $L_{j,a=3} - L_{j,a=1} \sim U(5{,}25)$		
	$t_{0,j,y}$	Age at which the length (in expectation) is zero in year y	Year		A8	
	$t_{0,j}$	Average age at which the length (in expectation) is zero	Year	$\frac{1}{\kappa_j} ln \left\{ \frac{e^{\kappa_j}\left(L_{j,1} - L_{j,3}\right)}{L_{j,1}e^{-2\kappa_j} - L_{j,3}} \right\}$		
	ε_y^t	Annual residuals about the age at which the length is zero		$N(0{,}2)$		
	ρ^t	Autocorrelation coefficient in these residuals		$U(-1{,}1)$		
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$U(0{,}3),\ a = 0{,}1{,}2^{+}$		Upper bound chosen to preclude unrealistically large lengths for very young fish
	$p_{j,y,q,l}^{com,S}$	Model predicted proportion-at-length l of component j in the directed catch and round herring bycatch during quarter q of year y	-		A31	
	$A_{j,y,q,a,l}^{com}$	Proportion of age a of component j sardine that falls in the length group l mid-way through quarter q of year y	-		A17	
	$P_{j,y,l}^{S}$	Model predicted proportion-at-length l of component j that are infected with the endoparasite, at the time of the November survey in year y			A29	

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Selectivity	$S_{j,l}^{survey}$	Survey selectivity-at-length l in the November survey for component j	-		A27	Some smaller fish escape through the trawl net
	S_{50}	Length at which survey selectivity is 50%	Cm	$U(2.5{,}20)$		
	δ	Inverse of slope of survey selectivity-at-length ogive when selectivity is 50%	-	$U(0.05{,}50)$		
	$S_{j,y,q,l}$	Commercial selectivity-at-length l during quarter q of year y of component j	-		A15	
	$S_{j,y,q,a}$	Commercial selectivity-at-age a during quarter q of year y of component j	-		A16	
	χ_j	Height of the Gaussian component for component j relative to the height of the logistic component	-	$U(0{,}1)$		
	$\bar{l}_{1,j}$	Mean of the Gaussian distribution for component j	Cm	$U(5{,}15)$		
	$\bar{l}_{2,j,y,q}$	Length at 50% selectivity in the logistic component for component j in quarter q of year y	Cm	$\bar{l}_{2,j,y,q} - \bar{l}_{1,j} \sim U(0{,}15)$		Estimated for four time periods 84-86, 87-97, 98-01, 02-18
	$(\sigma_1^{sel})^2$	Variance parameter of the Gaussian distribution	Cm	$U(2{,}7)$		
	$(\sigma_2^{sel})^2$	Variance parameter of the logistic distribution	Cm	$U(0{,}10)$		
Multiplicative bias	$k_{j,N}^S$	Multiplicative bias associated with the November survey of component j	-		A24	
	$k_{j,r}^S$	Multiplicative bias associated with the recruit survey of component j	-		A25 – A26	
	k_{ac}^S	Multiplicative bias associated with the hydro-acoustic survey	-	$ln(k_{ac}^S) \sim N(-0.311, 0.094^2)$		Appendix B of de Moor and Butterworth (2016)
	k_{cov}^S	Multiplicative bias associated with the coverage of the recruits during the recruit survey in comparison to the coverage of the biomass during the November survey	-	Uniform prior on logit transpose of k_{cov}^S, such that $0.3 \leq k_{cov}^S \leq 1$		Lower bound selected in discussions with scientists on these surveys and their field experience
	k_{covS}^S	Multiplicative bias associated with the coverage of the south component recruits in comparison to the west component recruits during the recruit survey		$U(0{,}1)$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Catch	$C^{S}_{j,p,y,q,a}$	Model predicted number of age a fish of component j caught during quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A20	
	$lcut_{y,m}$	Cut off length for recruits in month m of year y	Cm	de Moor *et al*. 2019		Differ by month and year as informed by the recruit surveys
	$C^{bycatch}_{j,p,y,q,a}$	Number of age a fish of component j bycaught in the anchovy-directed fishery in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A18	
	$C^{dir}_{j,p,y,q,a}$	Number of age a fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A19	
	$C^{dir}_{j,p,y,q,l}$	Number of length l fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y	Billions		A30	
	$F^{By}_{j,y,q,a}$	Fished proportion in quarter q of year y for age class a of component j, of bycatch in the anchovy-directed fishery	-		A21	
	$F_{j,y,q}$	Fished proportion in quarter q of year y for a fully selected age class a of component j, by the directed and round herring bycatch fisheries	-		A22	
Likelihood	$-lnL^{Nov}$	Contribution to the negative log likelihood from the model fit to the November survey biomass data	-		A33	
	$-lnL^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A34	
	$-lnL^{surpropl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A35	
	$-lnL^{compropl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A36	
	$-lnL^{surprev}$	Contribution to the negative log likelihood from the model fit to the November parasite prevalence-at-length data	-		A37	
	ϕ^{S}_{ac}	CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually rather than remain fixed over time	-	=0.227		Appendix B of de Moor and Butterworth (2016)
	$\left(\lambda^{S}_{j,N/r}\right)^2$	Additional variance (over and above $\left(\sigma^{S}_{j,y,Nov/rec}\right)^2$ and $(\phi^{S}_{ac})^2$) associated with the November/recruit surveys of component j	-	$U(0,10)$		

Table A1 (Continued).

Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
w_{propl}^{sur}	Weighting applied to the remaining survey proportion-at-length data	-	$= 0.5 \times 0.167$		To allow for autocorrelation[13]
$\sigma_{j,sur}^{S}$	Standard deviation associated with the survey proportion-at-length data of component j	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}\left(\sqrt{\hat{p}_{j,y,l}^{S}}-\sqrt{p_{j,y,l}^{S}}\right)^2}{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}1}}$[14]		Closed form solution
w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data		$= 0.5 \times 0.04$		To allow for autocorrelation[15]
$\sigma_{j,com}^{S}$	Standard deviation associated with the commercial proportion-at-length data of stock j	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}\left(\sqrt{\hat{p}_{j=1,y,q,l}^{comlS}}-\sqrt{\right.}}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}1}}$ $\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}\left(\sqrt{\hat{p}_{j=2,y,q,l}^{comlS}}-\sqrt{\right.}}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}1}}$	Closed form solution[16]	$\sigma_{j,com}^{S}$

[13] Based upon data being available ~6 times more frequently than annual age data which contain maximum information content on this.

[14] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.

[15] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this.

[16] A shorter range of lengths is used for the south component given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

Table A2. Assessment model data, detailed in de Moor *et al*. (2019).

Quantity	Description	Units / Scale	Shown in Figure
t_y^S	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\tilde{C}_{j,y,0bs}^S$	Number of juveniles of component j caught between 1 May and the day before the start of the recruit survey in year y	Billions	
$C_{j,y,m,l}^{RLF,fleet}$	Number of fish in length class l landed by $fleet$ in month m of year y of component$j$. $fleet = 1$ denotes the sardine directed fishery, $fleet = 2$ denotes the sardine bycatch with round herring (1984-2011) or ≥14cm sardine bycatch (2012-18) and $fleet = 3$ denotes the juvenile sardine bycatch with anchovy (1984-2011) or <14cm sardine bycatch (2012-18)	Billions	
$\hat{B}_{j,y}^S$	Acoustic survey estimate of biomass of component j from the November survey in year y	Thousand tons	Fig. 1
$\sigma_{j,y,Nov}^S$	Survey sampling CV associated with $\hat{B}_{j,y}^S$ that reflects survey inter-transect variance	-	Fig. 1
$\hat{N}_{j,y,r}^S$	Acoustic survey estimate of recruitment of component j from the recruit survey in year y	Billions	Fig. 2
$\sigma_{j,y,rec}^S$	Survey sampling CV associated with $\hat{N}_{j,y,r}^S$ that reflects survey inter-transect variance	-	Fig. 2
$\hat{p}_{j,y,l}^S$	Observed proportion (by number) of component j in length group l in the November survey of year y	-	Fig. 6
$\hat{p}_{j,y,q,l}^{S,com}$	Observed proportion (by number) of the directed catch and round herring bycatch of fish of component j and length group l during quarter q of year y	-	Fig. 9
$n_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested and found to be infected with the endoparasite	Numbers	Fig. 13
$N_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested for infection with the endoparasite	Numbers	Fig. 13